Somatosensory processing during movement observation in humans

S. Rossi,[1] F. Tecchio,[2] P. Pasqualetti,[3] M. Ulivelli,[1] V. Pizzella,[4] G-L. Romani,[4] S. Passero,[1] N. Battistini,[1] and P. M. Rossini [3,5]

[1]*Dipartimento di Neuroscienze, Sezione Neurologia, Università di Siena, Italy;* [2]*Istituto di Elettronica dello Stato Solido, CNR, Roma, Italy;* [3]*AFaR-CRCCS Divisione Neurologia, Ospedale Fatebenefratelli, Isola Tiberina, Roma, Italy;* [4]*Istituto di Tecnologie Avanzate Biomediche, Università di Chieti, Italy;* [5]*IRCCS Centro S. Giovanni di Dio, Brescia, Italy*

1 Introduction

Observation of movements involves similar firing of voluntary execution in a discrete portion of pyramidal neurons located in the ventral premotor cortex (area F5), both in primates [1,2,3] and humans [4,5,6,7].

Despite the importance of neural systems matching action observation and execution in the everyday life, little attention has been devoted to somatosensory processing during action observation, although the appropriateness of the sensory encoding is a pre-requisite to correctly understand, and reproduce, the just observed action.

Electro- (EEG) and magneto-encephalographic (MEG) recordings of spontaneous and evoked (SEP = somatosensory evoked potentials, and SEF = somatosensory evoked fields) activity in sensori-motor areas have provided so far information about primary (S1) and non primary (posterior parietal cortex-PPC and secondary-S2) somatosensory activation characteristics. There is evidence that sensory inputs reach motor and pre-motor areas too, both serially and via parallel pathways from thalamic relays.

Sensorimotor areas activity displays modality-specific modulation of different cerebral rhythms; the spontaneous ≈10 Hz and ≈20 Hz MEG activities cluster into the post-central cortex or along the pre-central gyrus [8], respectively, therefore reflecting different functional networks, the former being mainly linked with somatosensory cortical function and the latter being associated with predominant motor cortical function [9].

By coupling investigations of SEPs and SEFs (in the time domain) and of brain rhythms (in time and the frequency domains), it is therefore possible to explore with high spatial and temporal resolution complementary aspects of the whole cerebral activity, which embrace pure somatosensory processing and more complex sensorimotor integration mechanisms. The aim of the present study is to investigate whether and how the brain activity subserving both early and late sensory information is modified during action observation in humans.

2 Methods

2.1 Subjects and study design

Fifteen healthy, right-handed, fully informed volunteers (10 males, 5 females; age range 26-47 years) were enrolled in the study after the approval of the procedure by the Ethical Committees. Each subject participated to one or more experiments.

SEPs, SEFs and cerebral rhythms were recorded according to the following conditions, randomly intermingled between subjects:

"Relax": fixating a stable point on the front wall;

"Obs-grasp": observation of a grasping movement performed by one of the examiners with the right hand at about 0.5 Hz; the examiner was behind the subject, showing his right moving hand near the subject's own right hand;

"Obs-seq": observation of a sequence of finger movements performed with the right hand by one of the examiners at about 0.5 Hz. At the end of this task, the subject had to recognize the observed sequence;

"Calc.": mental calculation while fixing a stable point on the front wall: the subjects were asked to subtract seven from an assigned four-digit number. This condition was not run in MEG recordings.

"Move": the subjects were asked to move their right hand in accordance with a self-determined finger movement sequence, at a repetition rate of about 0.5 Hz.

2.2 SEPs

Subjects (10) lay on a reclining chair in a quiet room. The right median nerve was stimulated at the wrist with electric square wave pulses (0.9 Hz; 200 µsec) eliciting painless thumb oppositions. Brain responses were recorded with a commercially available electromyograph (Phasis-Ote Biomedica):

disk electrodes were firmly glued on the scalp with collodion at $C3_1$, P3 and bilaterally on precentral and frontal sites (6-7 cm in front and 2 cm lateral of Cz), where the N_{30} wave is mainly represented. The contralateral earlobe was the reference. Bandpass filter was settled between 3 Hz and 1.5 kHz and signals sampled at 4 kHz. Final waveforms were 250 artefact-free responses; signals were replicated at least twice to show the waveform reproducibility.
A further electrode was placed on the spinous process of the C7 vertebra (with an anterior neck reference), in order to measure the transit time of the sensory volley along the lemniscal system to SI [central conduction time (CCT)] and to constantly monitor the stability of the afferent volley entering the spinal cord in the different conditions. The CCT was evaluated in each subject by subtracting the latency of the spinal N_{13} from the peak of the N_{20} scalp response, which represents the marker of S1 activity.
The amplitude values of parietal (N_{20}) and frontal (N_{30} complex) waves were calculated from the maximal peak-to-peak differences.

2.3 SEFs and sensorimotor rhythms

Recordings were carried out with the 165-channel whole-scalp neuromagnetometer, operating at the Institute of Advanced Biomedical Technologies, University of Chieti, Italy. This system features 153 integrated magnetometers (8x8 mm^2 area) evenly distributed over the whole scalp, plus 12 channels for noise reduction. The overall system noise is better than 5 fT/√Hz above 1 Hz. Additional experiments were performed with a 28-channel system, which covers a scalp area of about 180 cm^2. Both systems operate in a magnetically shielded room (Vacuumschmelze GMBH).
SEFs were recorded in continuous mode during the "Relax", "Obs-grasp", "Obs-seq" and "Move" conditions previously described. SEFs were obtained by averaging 150 artefact-free trials. When the 28-channel sensor was used, it was centred on the C3 position for S1 recordings, and on the ipsilateral perisylvian region (2.5 cm above the T4 position) for S2. The right median nerve at wrist was electrically stimulated as before, with random interstimulus intervals (ISIs) ranging between 1.5 s and 2.5 s, because S2 responses are most frequently identifiable at these ISIs [10,11]. Signals were filtered between 0.48 and 250 Hz and sampled at 1 kHz. The exact head position with respect to the sensor was determined by 5 current-feeded coils, whose locations in space were digitized with reference to three anatomical landmarks that were used to define an individual coordinates system as follows: the x-axis through left and right preauricular points; outgoing right; y- ortogonal to x-axes and outgoing from nasion; and z-axes to obtain the right-hand coordinates system.
The strength of each SEF component was calculated with respect to a baseline level chosen as the mean value of the 5-15 ms post-stimulus epoch. Equivalent Current Dipole (ECD) characteristics (spatial coordinates and strength) were calculated using a moving dipole model inside a homogeneously conducting sphere. In the sensorimotor hand region, the first two peaks in the 15-50 ms post-stimulus epoch were considered (M20, M30). In the PPC and perisylvian S2 regions, the localization process was considered in the 70-150 ms interval. Localization results were accepted only if the explained variance was above 90%. ECD positions were expressed in the individual Cartesian coordinate system previously defined.
In agreement with Salmelin and Hari [12] the temporal evolution during "Relax", "Obs-grasp", "Obs-seq" and "Move" conditions of ≈10 and ≈20 Hz spectral components, was calculated by applying the temporal spectral evolution method (= TSE). In order to quantitatively assess both inhibition and rebound effects in the three conditions, the integral of areas below or above 3 standard deviations (SD) of the 300 ms pre-trigger epoch were taken from the most reactive channel, and percentual variations with respect to the "Relax" condition were calculated.

2.4 Statistical procedures

Since amplitude values usually do not follow a gaussian distribution and the small number of subjects did not allow us to check the appropriateness of data transformations, non-parametric analysis was chosen for statistical evaluation throughout the study. In particular, non-parametric ANOVA for repeated measures (Friedman test) with condition as within-subjects factor was applied to latency and amplitude values for each SEP and SEF component. Whenever a significant effect was found ($p < 0.05$), planned comparisons (Wilcoxon signed rank test) of "Obs-grasp", "Obs-seq", "Calc" and "Move" amplitude values versus "Relax" (as reference condition) were executed. Changes in cerebral rhythms were similarly approached. In addition, amplitude percentages (after logarithmic transformation of amplitudes) with respect to "Relax" (= 100%) were computed, in order to express the relative variations due to the different tasks. Percentage data were only used for graphical representation. Finally, correlations between SEF generator strength and rhythmic activity intensities were calculated by Spearman's rank coefficients (rho).

3 Results

3.1 SEPs: latencies and amplitudes

Peak latencies of pre- and post central SEP components did not significantly differ in the experimental conditions and also CCT values remained stable, with the maximal variability never exceeding the 5% of the basal value obtained during "Relax" (6.3 ± 0.3 ms).

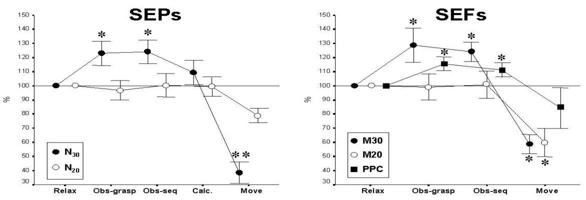

Figure 1: *The two diagrams represent the SEP (left side) and SEF (right side) behavior in the different experimental conditions. Amplitude or strength during "Relax" is considered as 100% (pooled subjects); variations are expressed as percentage change; vertical bars are one standard error. Note the significant increase (= asterisks) of the N_{30} SEP, M30 and PPC activation during both "Obs-grasp" and "Obs-seq" conditions and the significant reduction of these components during actual movements. There is no change in SEP waves between "Relax" and "Calc" (not performed in MEG recordings).*

The amplitude of the spinal component N_{13} (2.4±0.1 µV in "Relax") remained similar in every condition (2.5±0.1 µV in "Obs-grasp", 2.5±0.6 µV in "Obs-seq", 2.6±1.0 µV in "Calc." and 2.2±0.5 µV during "Move"), thus indicating a good stability of the amount of signal entering the spinal cord even during the actual movement. The diagram in Figure 1 shows the percentual variation of log-amplitude values of pre- and post-central SEP waves in the different experimental conditions (pooled data). Friedman non-parametric ANOVA indicated a significant effect of "Condition" on the N_{30} amplitude ($p<0.001$), while no changes were detectable on N_{20} component ($p = 0.219$). Planned comparisons (Wilcoxon signed ranks test) indicated that during the voluntary movement ("Move"), the amplitude of the pre-central complex significantly ($p = 0.008$) decreased with respect to "Relax" (3.6±1.8 µV). An opposite, but still selective, behaviour of the pre-central complex was detected both during "Obs-seq" and "Obs-grasp" conditions, with a significant amplitude increase of the frontal N_{30} (respectively, $p = 0.017$ and $p = 0.042$). The amplitude of the considered waves during "Calc." did not significantly differ from the other conditions.

3.2 MEG: SEFs cortical sources

Individual peak latencies of SEF components peaking around 20 and 30 ms (M20 and M30) did not vary across conditions.

Localization results of generators of M20 and M30 components in primary sensorimotor areas, and generators successively activated in PPC and in S2, did not show any significant variation across experimental conditions (Friedman test, $p>0.05$ consistently for x, y and z coordinates). This allowed to safely evaluate their ECD strength variations. The Friedman test showed that the M30 ECD strength significantly changed across conditions ($p = 0.023$, Fig.1-2). This overall significance was due to two opposite variations with respect to "Relax": increments during observation tasks (Wilcoxon test, $p = 0.043$ both in "Obs-grasp" and in "Obs-seq") and decrements during "Move" (Wilcoxon test, $p = 0.043$). It is worth noting that the above changes were consistently observed in each subject. SEFs-derived PPC generators also showed a significant dependence on conditions (Friedman test, $p = 0.022$), since both observation tasks produced stronger ECDs (Wilcoxon test, $p = 0.043$ both in "Obs-grasp" and in "Obs-seq"). No significant variation was observed during "Move" ($p = 0.50$).

For S2 ECD strength as well, we found consistent patterns in all subjects. However, for this area, only decrements vs. "Relax" could be observed in the three conditions, although the lack of data for one subject did not allow us to obtain significant results (Friedman test, $p = 0.058$, Fig.2).

3.3 MEG: cerebral rhythms

The mu-rhythm reacted less than beta-rhythm to somatosensory stimulation. Both the post-stimulus inhibition (100-400 ms) and the following rebound (400-600 ms) of the rhythmic activity in the parietal region (≈10 Hz) during "Obs-grasp" and "Obs-seq" were consistently decreased in all subjects respect to "Relax". The intensity of the ≈20 Hz beta-activity rebound significantly decreased during "Obs-grasp"

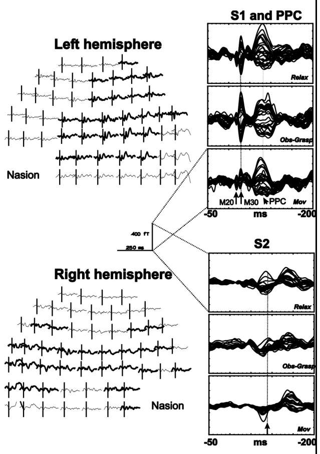

Figure 2: *Left side: whole-head hemispheric SEF data-set in one representative subject during the basal condition ("Relax") (left side):. Note that the M20 –marker of S1 activation- is stable, while the M30 and the 80 ms PPC component are potentiated during action observations and reduced during execution of hand movements. The S2 source, which is evident during "Relax", tends to disappear both during observation and movement execution.*

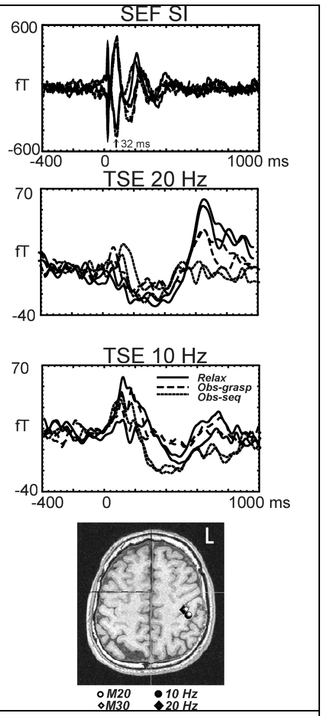

Figure 3: *From the top, the SEF recorded in the left primary sensorimotor area, the TSE of the ≈20 Hz and the TSE of the ≈10 Hz rebounds in one representative subject. The two most reactive channels are shown. Individual MRI showing the localization of the ≈20 Hz and ≈10 Hz activity together with the sources of M30 and M20. The ≈20 Hz activity and the M30 cluster both in the anterior wall of the central sulcus; the ≈ 10 Hz and the M20 cluster in the posterior wall of the central sulcus.*

and "Obs-seq" (Wilcoxon test, $p = 0.04$ and $p = 0.08$, respectively, Fig. 3). The ≈10 Hz inhibition significantly increased ($p = 0.04$) during "Obs-grasp", while during "Obs-seq" it increased only in 2 out of 5 subjects (Fig. 3).

The decrement of ≈20 Hz rebound during observation tasks vs. "Relax" was inversely correlated with the strength increase of the M30 SEF component [Spearman rho = -0.90 for "Obs-grasp", rho = -0.87 for "Obs-seq", $p < 0.05$], but not with the behaviour of the strengths of the S1, PPC and S2 sources.

4 Discussion

In line with a previous study [7], we found a decreased rebound of the ≈20 Hz MEG beta-rhythm, confirming that intrinsic motor cortex activity is modified during action observation.

The selective amplitude reduction of the pre-central N_{30} complex during the "Move" condition is explainable with the "gating effect", a partial "physiological" suppression of the sensory information reaching pre-central areas during movement execution. Such "centrifugal" gating mechanisms are possibly related to corollary discharges of the motor program.

The potentiation of pre-central SEP/SEF waves during observation seems mainly related to mechanisms of storage and encoding of the subject's somatosensory information, connected exclusively with the observed movement and regardless of its complexity. This is in line with the "direct matching hypothesis", put forward in a recent fMRI study to explain cortical mechanisms of the human observation/imitation system [13], and with the significant activation of the SMA found in a PET study when subjects observed meaningful actions [14].

The higher activation of the PPC source during observed actions versus "Relax" (Fig. 2 and 3) fits nicely with previous neuroimaging studies [6, 14, 13] and is consistent with the fact that parieto-frontal circuits represent the basic elements of the cortical motor system and that they contribute in parallel to specific sensorimotor elaboration [15].

Somatosensory areas involvement in executed and observed movement suggest that such anatomo-functional coupling may rely on the activity of the "mirror neurons" system described in monkeys, whose functional relevance has been recently postulated for humans' everyday life. Their action may be exerted at-distance from their anatomical location through dense and reciprocal connections with SMA and PPC. Therefore, this system may exert a modulatory activity that is not limited to motor output changes (4), as previously thought. Instead, the systems fully embrace those early sensory processes (i.e., few tens of milliseconds) that take place between the thalamus, pre-central and PPC areas, and leave unmodified the functionality of the parallel sensory pathway directed to S1, which do not seem to be involved in action observation mechanisms.

Acknowledgements

The authors wish to thank Mrs. Matilde Ercolani (MEG recordings) and Mr. Benito Vecchiarelli (SEP recordings) for their excellent technical assistance.

References

1. G. Di Pellegrino, L. Fadiga, L. Fogassi, V. Gallese, and G. Rizzolatti, "Understanding motor events: a neurophysiological study", *Exp. Brain Res.* **91**,176-180, 1992.
2. V. Gallese, L. Fadiga, L. Fogassi, and G. Rizzolatti, "Action recognition in the premotor cortex", *Brain* **119**, 593-606, 1996.
3. G. Rizzolatti, L. Fadiga, V. Gallese, and L. Fogassi, "Premotor cortex and the recognition of motor actions", *Cogn. Brain Res.* **3**, 131-141, 1996.
4. L. Fadiga, L. Fogassi, G. Pavesi, and G. Rizzolatti, "Motor facilitation during action observation: a magnetic stimulation study". *J. Neurophysiol.* **73**, 2608-2611, 1995.
5. G. Rizzolatti, L. Fadiga, M. Matelli, V. Bettinardi, E. Paulesu, D. Perani, and F. Fazio, "Localization of grasp representations in humans by PET. 1. Observation versus execution", *Exp. Brain Res.* **111**, 246-252, 1996.
6. J. Decety, J. Grezes, N. Costes, D. Perani, M. Jeannerod, E. Procyck, F. Grassi, and F. Fazio, "Brain activity during observation of actions. Influence of action content and subject's strategy", *Brain* **120**, 1763-1777, 1997.
7. R. Hari, N. Forss, S. Avikainen, E. Kirveskari, S. Salenius, and G. Rizzolatti, "Activation of human primary motor cortex during action observation: a neuromagnetic study", *Proc. Natl. Acad. Sci.* **95**, 15061-15065, 1998.
8. R. Salmelin, M. Hämäläinen, M. Kajola, and R. Hari, "Functional segregation of movement-related rhythmic activity in the human brain", *Neuroimage* **2**, 237-243, 1995.
9. R. Hari and R. Salmelin, "Human cortical oscillations: a neuromagnetic view from the skull", *Trends Neurosci.* **20**, 44-49, 1997.
10. R. Hari, J. Karhu, M. Hämäläinen, J. Knuutila, O. Salonen, M. Sams, and V. Vilkman, "Functional organization of the human first and second somatosensory cortices: a neuromagnetic study", *Eur. J. Neurosci.* **5**, 724-734, 1993.
11. F. Mauguiere, I. Merlet., N. Forss, S. Vanni, V. Jousmäki, P. Adeleine, and R. Hari, "Activation of a distributed somatosensory cortical network in the human brain. A dipole modeling study of magnetic fields evoked by median nerve stimulation. Part I: Location and activation timing of SEF sources", *Electroencephalogr. Clin. Neurophysiol.* **104**, 281-289, 1997.
12. R. Salmelin and R. Hari, "Spatiotemporal haracteristics of sensorimotor neuromagnetic rhythms related to thumb movement", *Neuroscience* **60**, 537-550, 1994.
13. M. Iacoboni, R.P. Woods, M. Brass, H. Bekkering, J.C. Mazziotta, and G. Rizzolatti, "Cortical mechanisms of human imitation", *Science* **286**, 2526-2528, 1999.
14. J. Grezes, N. Costes, and J. Decety, "Top-down effect of the strategy on the perception of biological motion: a PET investigation", *Cognit Neuropsychol* **15**, 553-582, 1998.
15. G. Rizzolatti, G. Luppino, and M. Matelli, "The organization of the cortical motor system: new concepts". *Electroencephalogr Clin Neurophysiol* **106**, 283-296, 1998.